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# Resilience of 'Nightingale' hospital wards in a changing climate

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The National Health Service (NHS) Estate in England comprises more than 30 Mm<sup>2</sup> with 18.83 Mm<sup>2</sup> of acute hospital accommodation on 330 sites. There is concern about the resilience of these buildings in a changing climate, informed by the experience of recent heatwaves. However, the widespread installation of air conditioning would disrupt the achievement of ambitious energy reduction targets. The research project 'Design and Delivery of Robust Hospital Environments in a Changing Climate' is attempting to estimate the resilience of the NHS Estate on the basis of current and projected performance, using an adaptive comfort model. This paper presents results relating to a 1920s traditionally built block with open 'Nightingale' wards, a representative type. The paper demonstrates the relative resilience of the type, and illustrates a series of light-touch measures that may increase resilience while saving energy.

**Practical application:** The results presented in this paper will be of value to NHS Trusts: Estates staff charged with operating buildings as well as Boards and others involved in decision-making. It will also find an audience with policymakers in central government and the Department of Health, as well as those who own, operate or are tasked with working on non-domestic buildings with heavy traditional construction.

## 1 Introduction

'Nightingale' hospital wards are open-plan dormitories for 24–30 patients. They were the dominant form of UK hospital ward before 1948, and a significant number remain in use. In England, 22% of National Health Service (NHS) acute hospital buildings pre-date 1948,<sup>1</sup> and on some sites the majority of wards are of this type. However, Nightingale

wards are now considered undesirable by the Department of Health (DH), which reports that they offer 'very little personal privacy or peace'.<sup>2</sup> The DH called in 2001 for Nightingale wards to be subdivided into bays.<sup>3</sup> A growing call for single en-suite rooms on the grounds of privacy and infection control has added to the debate, as the dimensions of Nightingale wards often do not support efficient conversion into single rooms. There is thus pressure to replace them. In the post-2008 economic climate, however, the possibility of wholesale replacement is much diminished. Many of these wards will therefore remain in use for the foreseeable future.<sup>4</sup>

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Figures 3–13, 15 and 16 appear in color online:  
<http://bse.sagepub.com>

This paper presents the findings of an investigation into a particular and previously unexplored property of this building type, its inherent resilience to high external temperatures, which are predicted to be more prevalent in the future. It takes as working examples two Nightingale wards at Bradford Royal Infirmary, considering their resilience and proposing adaptive strategies to enhance it. The work was carried out as part of the research project 'Design and Delivery of Robust Hospital Environments in a Changing Climate', funded by the UK Engineering and Physical Sciences Research Council and the Department of Health. The project is investigating the resilience of the NHS Retained Estate and proposing economical and resilient strategies for its adaptation in a changing climate to maintain what current guidance considers acceptable thermal conditions. The NHS faces a challenge: how to deliver safe environments in a changing climate whilst meeting ambitious carbon reduction targets. The perhaps obvious strategy of fully air conditioning more NHS buildings is unlikely to deliver both results. Within the total NHS Estate in England of more than 30 Mm<sup>2</sup> (million square metres), there are 330 acute hospital sites with a gross floor area of 18.83 Mm<sup>2</sup> of which at least 8.3 Mm<sup>2</sup> is occupied by patients.<sup>1</sup> The NHS reports that it generates 18% of the carbon emissions of the UK non-domestic stock, 25% of UK public sector emissions, and 3% of total UK emissions.<sup>5</sup> In a typical UK hospital, 44% of the energy used can be attributed to air and space heating.<sup>6</sup> NHS organisations have ambitious targets for delivered energy of 35–55 GJ/100 m<sup>3</sup> in new buildings and 55–65 GJ/100 m<sup>3</sup> when refurbishing existing facilities for all building uses (including space heating, hot water, lights, appliances, catering).<sup>6</sup> However, the energy use of the majority of NHS Trusts in England is significantly higher, being in the range of 44.8–98.0 GJ/100 m<sup>3</sup> for 2004/2005 peaking at 125 GJ/100 m<sup>3</sup>.<sup>7</sup>

The health implications of a changing climate add to the challenge. UK heatwaves in 2003 and 2006 saw elevated levels of mortality<sup>8</sup> principally among the elderly and chronically ill. Such people are likely to be present in hospitals, alongside others unable to take action in the face of high temperatures including young children, the bed-bound, and those with mental illnesses.<sup>9</sup> The NHS has a fundamental duty of care and must provide a safe and comfortable environment for patients and visitors and staff (1.3 million employees, 5% of the UK workforce). It has acquired the role of offering a 'safe haven' for the vulnerable. High temperatures can affect certain pharmaceutical products as well as the functioning of computers and medical diagnostic equipment. Guidance suggests that naturally conditioned wards should not exceed 28°C for more than 50 occupied hours per year.<sup>10</sup>

The Department of Health advocates natural ventilation for non-critical spaces including wards and offices,<sup>10</sup> but concerns about infection control, worries about security and safety at operable windows, and a risk-averse procurement environment all act as barriers to its implementation.<sup>11</sup> There are few examples of the application of innovative passive cooling strategies in hospitals, even theoretically.<sup>9,11</sup> Thus although the NHS Heatwave Plan advocates a 'passive approach' to coping with heatwaves, it also suggests that the NHS should 'target vulnerable areas (patients, medications, IT) with air conditioning'.<sup>8</sup> This paper is about patient spaces.

## **2 The Nightingale ward as a recurrent hospital building type**

The first use of the 'Nightingale' ward in British hospital design dates from the 1860s, although its roots are found in 18th-century French hospitals.<sup>12</sup> It was advocated by various figures, not least Florence Nightingale, nurse, reformer and writer.

**Table 1** Nightingale ward, key characteristics.

|                        |   |
|------------------------|---|
| Orientation and layout | Typically north/south pavilions, with separate 'sanitary tower' to one side, accessed via ventilated lobby. From 1920s, many had south-facing open balcony.                                     |
| Typical dimensions     | 23.7 m long × 7.9 m wide × 3.6 m tall; 38–58 m <sup>3</sup> per patient<br>(75 feet long × 26 feet wide × 12 feet tall; 1000–1500 cu.ft per patient)  |
| Ventilation            | Type evolved to deliver natural cross-ventilation; up to 30 ach <sup>-1</sup> via windows and openings <sup>13</sup>  |
| Heating                | Stoves and fires supplemented by low-pressure hot water systems in early 20th century.<br>Temperatures locally set but literature suggested temperature of at least 60°F (15.5°C) <sup>26</sup> |

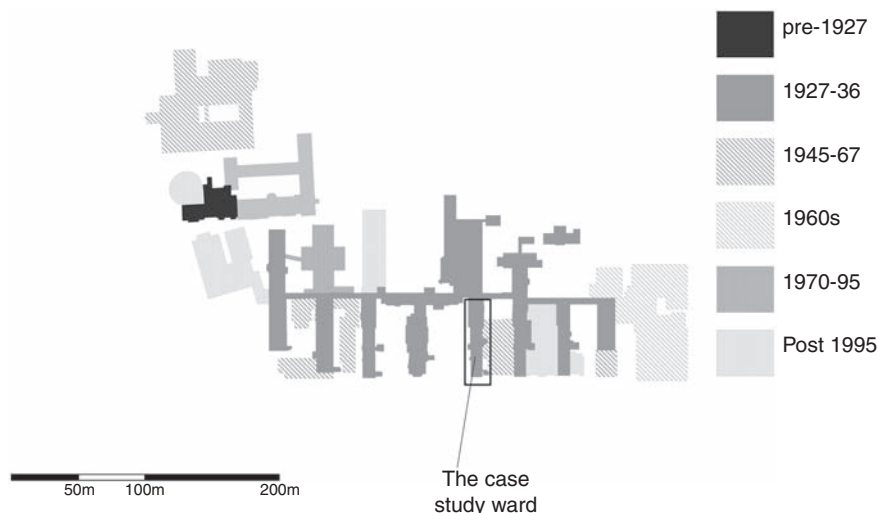
Nightingale's experience during the Crimean War of 1853–1856 suggested that hospital planning could significantly affect the incidence of cross-infection, believed to be at least partly the result of bad ventilation. Wards arranged as long, rectangular single-storey blocks, cross- and stack-ventilated by tall opposing windows, seemed to yield the most benign environments. Recent computational fluid dynamic modelling work has indeed demonstrated that significant rates of air change can be achieved.<sup>13,14</sup> As developed in the UK in the late 19th century, pavilions typically comprised several storeys, hence the reliance on cross-ventilation, as in the example of St Thomas', London (1868). A more sophisticated single-storey version, top-lit and mechanically ventilated, was developed in the Royal Victoria Hospital, Belfast (1899).<sup>15</sup> There was until the 1960s no national design guidance for hospitals, but some common patterns are recorded in Table 1.

### 3 Bradford Royal Infirmary

Bradford Royal Infirmary moved to new buildings on the city's western outskirts between 1927 and 1937.<sup>16</sup> The new hospital was a typical 'Nightingale' example with parallel four-storey ward blocks projecting south from a long east/west spine corridor; two wards on adjacent floors in one of these pavilions are the focus of this paper (Figure 1). Walls were load-bearing, of stone, c.500 mm thick, comprising 150 mm stone outer skin and 350–400 mm inner skin with some rubble infill; roofs were flat. Each

pavilion, as originally designed, accommodated on each floor 25–28 patients in the main part of the ward in a space 33.8 metres long by 8.2 m wide by 4.2 m floor to underside of structural soffit (110 ft × 22 ft × 13 ft 9 in.), with a small number of single and double bedrooms and other ancillary spaces located at the northern end of the pavilion. Sanitary facilities were set to the east. The design provided 20 m<sup>2</sup> per bed.<sup>17</sup> Windows were 'Crittall' type steel units of two types, with opening casements below a high-level hopper or with three top-hung 'hopper' windows opening in and out below a fixed lower casement. The hoppers had a double folding hinge enabling almost all free area to be realised (Figure 2). Ventilators below the windows ducted air behind the radiators.

The wards being studied have, like many others on the site, been subdivided within recent years to create three separate bedded areas, allowing gender segregation and reducing their 'institutional' quality, and beds now can be curtained off. Suspended ceilings have been installed, reportedly to reduce the heated volume. Windows have been replaced with thermally broken aluminium-framed double-glazed units with significantly reduced opening area with only the middle section being operable; as is recommended by guidance<sup>18</sup> it is limited to 100 mm. The result is a significant reduction in the ability to provide natural ventilation, although, interestingly, the guidance suggests that larger openings could be provided for use in very hot periods. The originally open balconies at the ends of the wards have been glazed in to provide



**Figure 1** Bradford Royal Infirmary, site plan in 2011 with key building dates.

dayrooms. An ongoing programme of work is adding 120 mm of insulation to the roof to achieve a  $U$ -value of  $0.24 \text{ W/m}^2\cdot\text{K}$ ; the roofs already had 75 mm insulation during the period being reported here ( $U$ -value of  $0.3 \text{ W/m}^2\cdot\text{K}$ ). The below-window ventilators have been blocked; the convectors are modern replacements of the original 'hospital' radiators. There is no mechanical ventilation.

## 4 Performance of existing wards

### 4.1 Internal temperatures

The internal temperatures in four distinctly different spaces are currently being recorded at hourly intervals using Hobo U12, Hobo pendant and Tiny Tag loggers.<sup>a</sup> In addition to the Nightingale wards, a number of other ward types have been monitored on the site. Although different loggers were used, they were all calibrated prior to monitoring. The difference between them for the same space temperature is less than  $0.2^\circ\text{C}$ . There are two

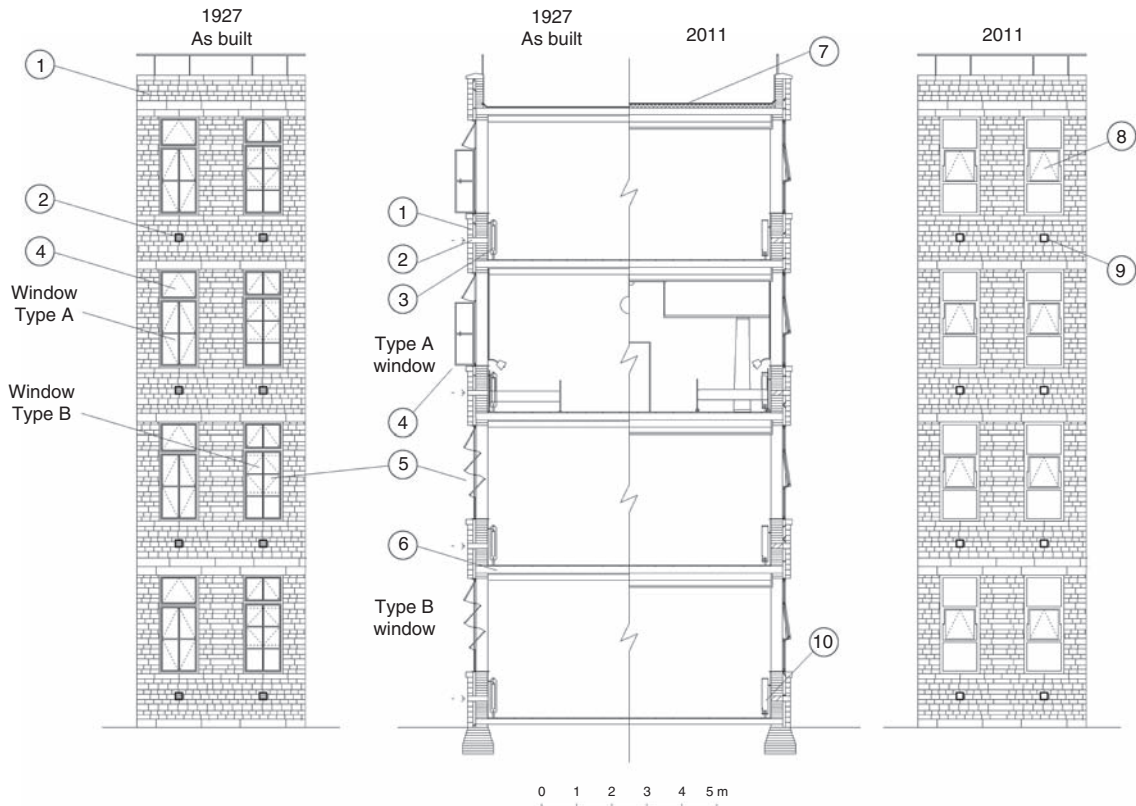
monitored spaces in Ward 8 on the 2nd floor (Figure 3(a)); one has two beds and one has 24 beds. There are two spaces in Ward 9 on the 3rd floor (Figure 3(b)), i.e. one Administration room and a 24-bed ward. There were two recorded temperatures in the twin bed room and the Administration room and eight in each ward. Ward 9 was internally partitioned but with openings between each zone. Ward 8 was partitioned in late October 2010.

The internal temperatures reported here are for a 69-day period from 1 June to 11 August 2010. The study uses weather data from the Bingley station which is the closest Meteorological Office site to the Infirmary, being approximately 4 miles to the Northwest. During the monitoring period, the ambient temperature was not especially warm, reaching a maximum value of just  $24.1^\circ\text{C}$  (see sections 4.2 & 5). In mid-June, night-time lows of just over  $5^\circ\text{C}$  were recorded. The peak global solar radiation intensity, which was predicted from the recorded cloud cover at the Bingley, was around  $750 \text{ W/m}^2$ .

Despite the partitions the internal temperatures were rather similar throughout Ward 8

<sup>a</sup>The temperature recorded approximates to air temperature, but must include an unknown radiant component.





**Figure 2** Typical Nightingale pavilion, Bradford Royal Infirmary, as designed/built 1927 and as currently.

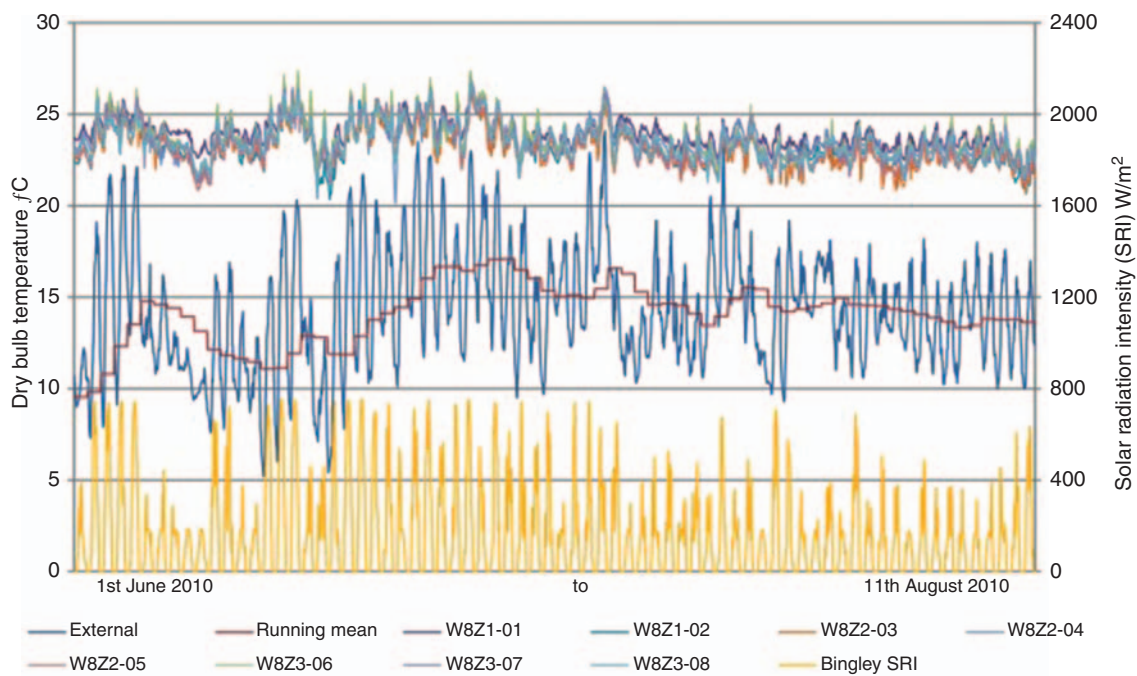
1: Solid masonry wall, c.500 mm thick inner brick, c.75 mm rubble infill, 150 mm coursed ashlar; 2: Airbricks to vents behind HW radiators; 3: Hot water 'hospital' radiator; 4: 'Crittall' type steel windows: Type 'A' with upper light comprising outward-opening hopper and lower side-hung casements, 3.025 m<sup>2</sup> max free area; 5: 'Crittall' type steel windows: Type 'B' with three stacked hopper windows providing 2.48 m<sup>2</sup> max free area; 6: Intermediate floors have unusually thin slab; facilities staff report embedded timber beams and that loading capacity is at maximum); 7: 75 mm extruded polystyrene insulation; 8: 3-light aluminium-framed thermal break windows installed 1990s, centre light opening restricted to 100 mm; 9: Ventilators blocked; 10: Hospital radiators replaced by convector heaters.

(Figure 4), across all 8 measuring points the temperature only varied from 20.1°C to 27.4°C with a mean of 23.7°C. The mean night-time temperature was 23.2°C and the maximum diurnal swing recorded was just 5.2°C (Table 2). The temperatures in Ward 9 were similar (Figure 5) but, due to occasional higher temperatures being recorded by the sensors on the inter-zone partitions and low temperatures being recorded on some nights, especially by a sensor close to a window (W9Z2-03, Figure 3(b)), the range was a little greater (Table 2). The two

smaller rooms (Figures 6 and 7) displayed similar temperatures to the wards but both had a lower maximum diurnal variation than the wards; perhaps because even if windows are left open at night, ventilation is less effective – being single sided rather than cross ventilated as in the wards. Overall therefore it is evident that the temperatures in all the spaces were rather well controlled and well within the wide range recommended for wards by Health Technical Memorandum HTM03-01 of 18°C to 28°C,<sup>10</sup> despite reduced ventilation capacity.



**Figure 3** The Nightingale Wards showing temperature measurement locations: (a) Ward 8; (b) Ward 9.

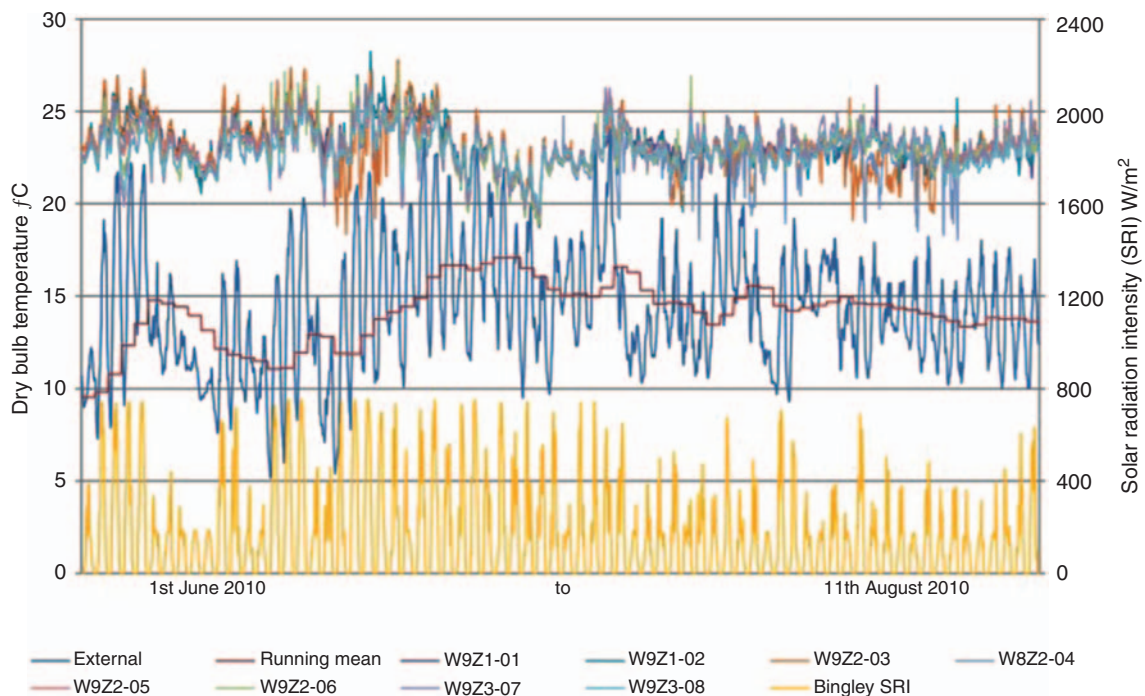


**Figure 4** Measured temperatures in Ward 8 and ambient conditions.

**Table 2** Summary of monitored internal temperatures.

| Ward | Space      | Maximum temperature (°C) (24 h) | Minimum temperature (°C) (24 hours) | Mean daytime temperature (°C) (7:00 to 20:00) | Mean night-time temperature (°C) (21:00 to 6:00) | Maximum diurnal range (K) | Hours over 25°C (24 h) | Hours over 28°C (24 h) | Hours over 24°C (21:00 to 6:00) | Hours over 26°C (21:00 to 6:00) |
|------|------------|---------------------------------|-------------------------------------|---|--|---------------------------|------------------------|------------------------|---------------------------------|---------------------------------|
| 8    | Ward 8     | 27.4                            | 20.1                                | 23.7  | 23.2   | 5.2                       | 167 (9.6%)             | 0                      | 155 (21.5%)                     | 3                               |
|      | 8-twin bed | 26.5                            | 19.1                                | 23.2  | 23.0   | 3.5                       | 67 (3.9%)              | 0                      | 149 (20.7%)                     | 0                               |
| 9    | Ward 9     | 28.2                            | 18.0                                | 23.4  | 22.7   | 6.9                       | 106 (6.1%)             | 0                      | 73 (10.1%)                      | 1                               |
|      | 9-admin    | 26.1                            | 18.2                                | 22.7  | 22.4   | 3.9                       | 27 (1.6%)              | 0                      | 80 (11.1%)                      | 0                               |

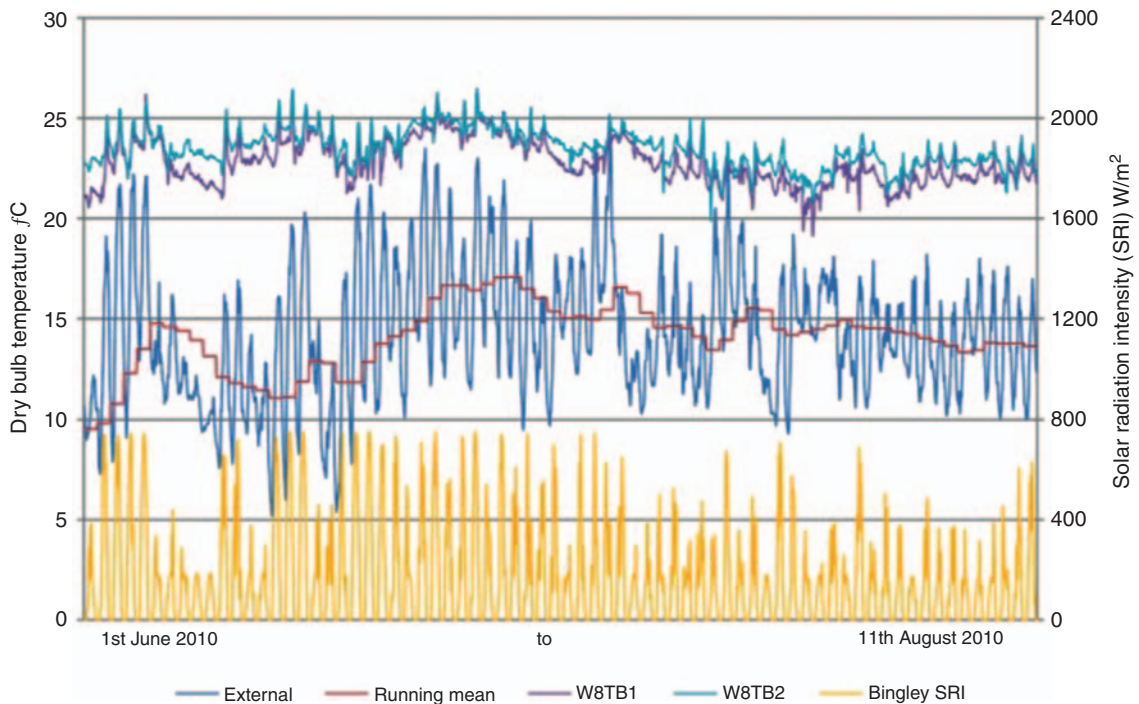
Total number of hours: 1728 (69 days); Total number of night-time (21:00 to 6:00) hours: 720.

**Figure 5** Measured temperatures in Ward 9 and ambient conditions.

A number of criteria have been proposed to minimise the risk of overheating in hospital wards, which have been extensively reviewed and critically assessed elsewhere.<sup>9,19</sup> Essentially, an upper limit of 28°C dry-bulb temperature is described in HTM03-01, and 28°C operative temperature by the CIBSE

Guide A,<sup>20</sup> although both are offered for the purposes of evaluating predictions of models rather than measured temperature. It is evident (Table 2) that the wards are well within these thresholds, indeed there were at most just 9.6% of recorded hours above 25°C, which the CIBSE Guide notes is an





**Figure 6** Measured temperatures in Ward 8 twin bed space and ambient conditions.

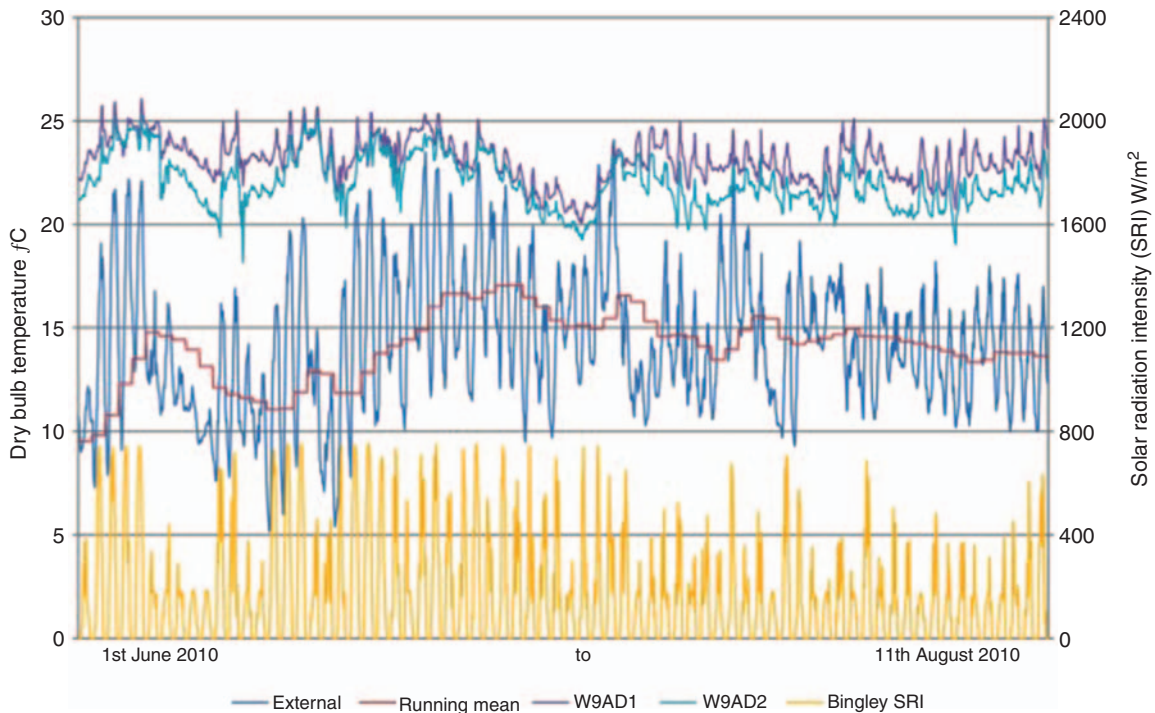
‘acceptable temperature’ above which individuals will start to feel increasingly warm and uncomfortable.<sup>20</sup> At night, 24°C was exceeded frequently in all four spaces – this is the temperature at which the CIBSE Guide suggests quality of sleep starts to decrease in normal health adults. However, 26°C, the temperature that the CIBSE guide says should not be exceeded, was exceeded on just 3 h and 1 h in Wards 8 and 9, respectively (Table 2).

It has been argued that the recently published thermal comfort standard BS EN 15251,<sup>21</sup> provides a superior framework for evaluating thermal comfort in free-running hospital spaces where temperature control is primarily effected by opening windows.<sup>19</sup> This is because:

- it is equally applicable to measured as well as predicted temperatures;
- it takes account of human adaptation to the

warmer ambient temperature, and thus our *preference* for higher temperatures in warm summer spells, and so seems suited to assessing comfort in a future warmer climate;

- it explicitly enables comfort to be assessed in spaces with different occupant types, with Cat I spaces being those occupied by ‘very sensitive and fragile persons with special needs’ (as in a hospital wards), Cat II being those with ‘normal occupancy’, nurses stations and consulting rooms perhaps and Cat III for even less important spaces, circulation and waiting perhaps;
- it uses operative temperature as the basis for limiting the allowable temperatures and so can account for known factors that impact on human thermal comfort; and
- it enables the category that is appropriate for any space, and the allowable exceedance of that category’s threshold temperatures,



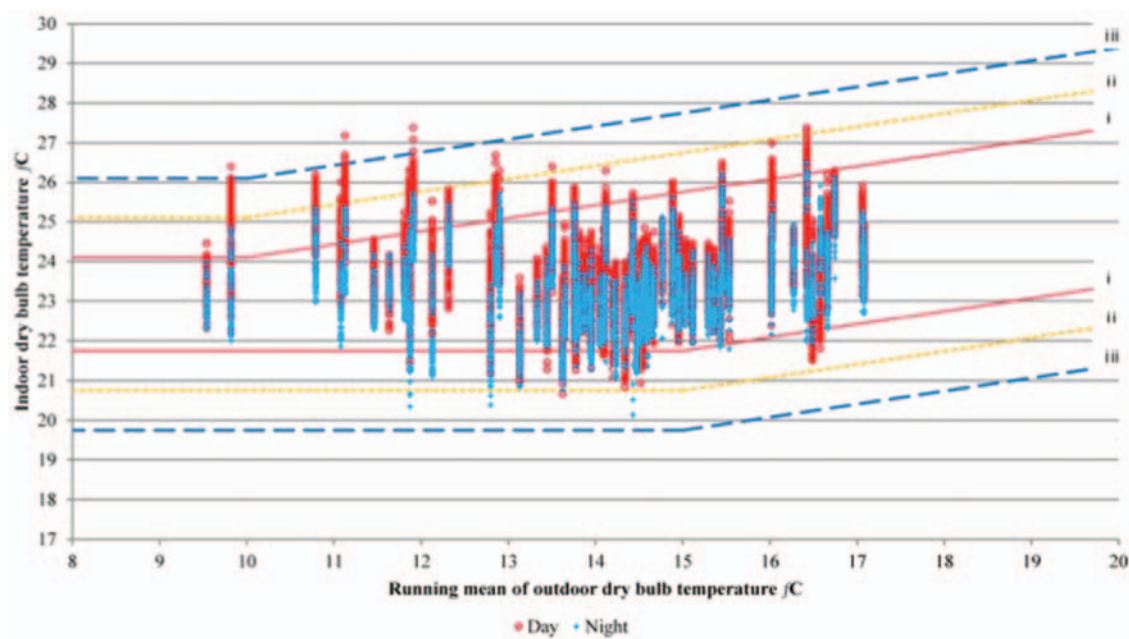
**Figure 7** Measured temperatures in Ward 9 administration office and ambient conditions.

to be determined by ‘national regulations or individual project specifications’.

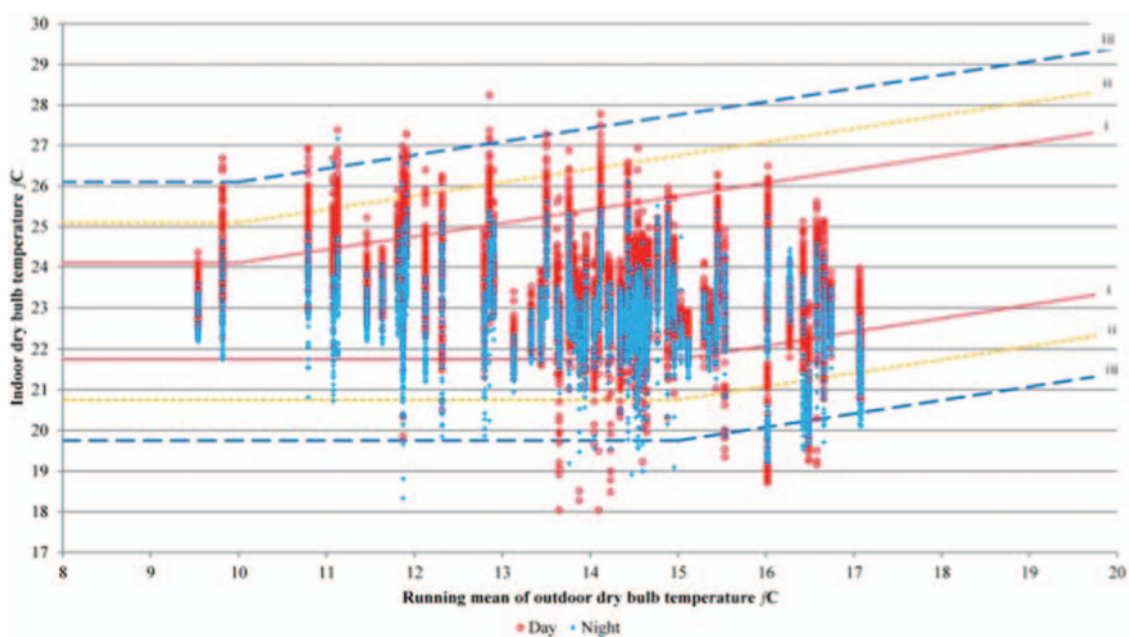
The thresholds of operative temperature increase with the exponentially weighted running mean of the ambient temperature, which is calculated such that yesterday’s mean temperature is rather influential on our perception of the temperature that is comfortable, the day before yesterday less so, and so on. The calculated running mean temperature for the monitoring period is shown on Figures 4 to 7. The three BSEN15251 category limits are shown with the measured day and night-time temperatures overlaid in Figures 8 to 11.

The BSEN15251 adaptive thermal comfort envelopes are not applicable for the heating season and so the standard provides a table for the temperatures to be used for the upper thresholds at running mean temperatures below 10°C and lower thresholds below

15°C; unfortunately spaces of the type found in hospitals are not listed. Here, therefore, the category thresholds have simply been continued horizontally from 10°C and 15°C, which gives lower and upper thresholds for Cat I of 21.8°C and 24.1°C, Cat II 20.8°C and 25.1°C and Cat III 19.8°C and 26.1°C. Many of these values relate quite well to CIBSE tabulated winter values for conditioned spaces:<sup>20</sup> bed head and consulting rooms 22°C to 24°C (cf. Cat I limits), offices 21°C to 23°C (cf. Cat II lower limit), circulation in wards and general waiting areas 19°C to 24°C (cf. Cat III lower limit). Interestingly the winter temperatures for nurses’ stations are given as 19°C to 22°C, rather cooler than for bedded areas of wards. The upper limits of Cat II and Cat III drawn using this method (25.1°C and 26.1°C, respectively) are rather high and spaces running at these temperatures are likely to be unnecessarily warm and energy inefficient.



**Figure 8** Comparison of measured temperatures with BSEN15251 comfort envelopes: Ward 8.



**Figure 9** Comparison of measured temperatures with BSEN15251 comfort envelopes: Ward 9.

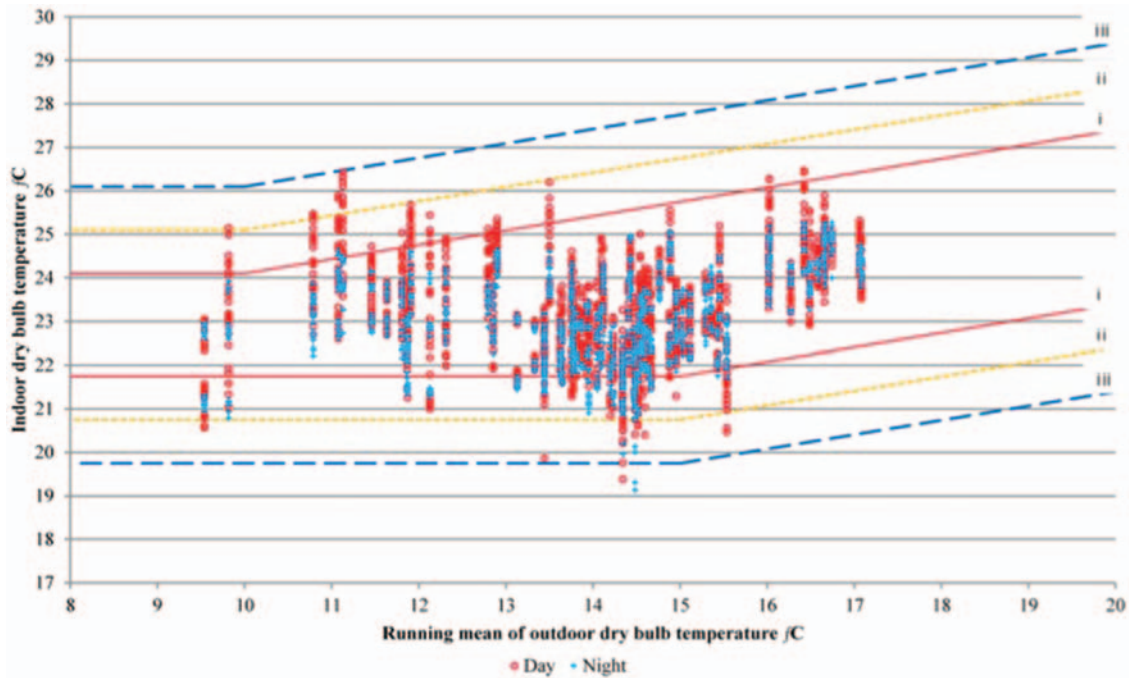


Figure 10 Comparison of measured temperatures with BSEN15251 comfort envelopes: Ward 8 twin bed room.

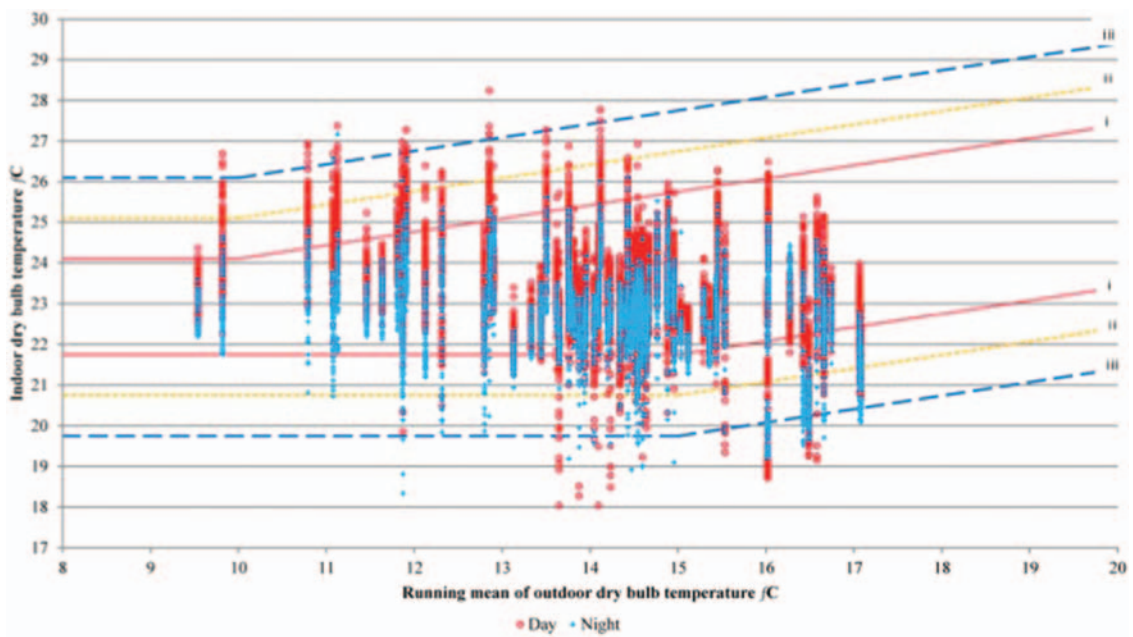
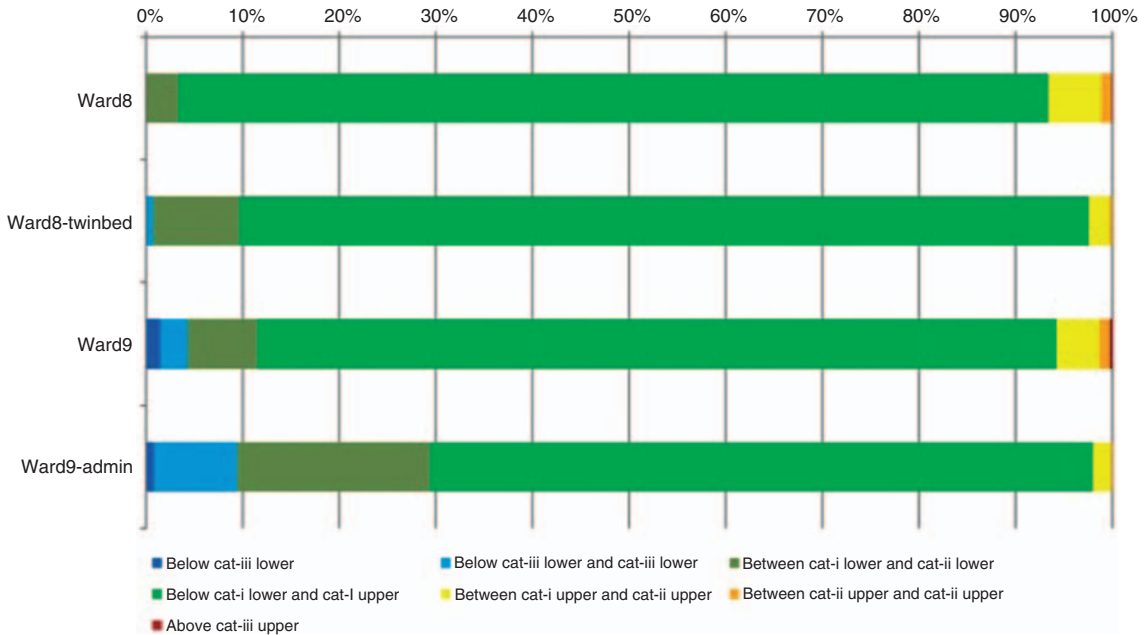


Figure 11 Comparison of measured temperatures with BSEN15251 comfort envelopes: Ward 9 administration office.





**Figure 12** Percentage of all measured values in each BSEN15251 category.

The temperatures measured by each sensor are plotted against the running mean of ambient temperature, with the category envelopes overlaid, in Figures 8 to 11. For the wards there are therefore  $8 \times 24$  values for each value of the running mean. The percentage of time for which each space is operating within each of the category limits is summarised in Figure 12. From this figure it is evident that the three bedded areas operate within the Cat I limits for the great majority of the time, with 7% of the Ward 8 temperatures exceeding the Cat I upper threshold, 6% of Ward 9 temperatures and 2% of the twin bedded room temperatures. Interestingly, most of these higher temperatures occur at the lower running mean temperatures indicated by the standard suggesting that, by reducing the heating set point, energy might be saved without compromising comfort.<sup>b</sup>

<sup>b</sup>Here and elsewhere comfort is as defined by the BSEN15251 categories and not by patient, staff or visitor perceptions.

There is no evidence of overheating due to higher ambient temperatures and solar gain, which is as one might expect given the rather low summertime temperatures experienced in Bradford during the monitoring period. The Administration space, like the wards, tends to be overly warm when the heating system operates yet broadly within the Cat II envelope when it does not. Overall fewer than 2% of the recorded temperatures exceed the Cat I upper threshold (Figure 12).

From the measurements alone, it is difficult to draw conclusions about the inherent resilience of the Nightingale wards to elevated ambient temperatures because the ambient temperatures were quite low. To explore this matter further and to assess the typical energy demands of the wards a calibrated dynamic thermal model was used.

## 4.2 Energy use and CO<sub>2</sub> emissions

To predict the annual energy demands and resulting CO<sub>2</sub> emissions of the Nightingale



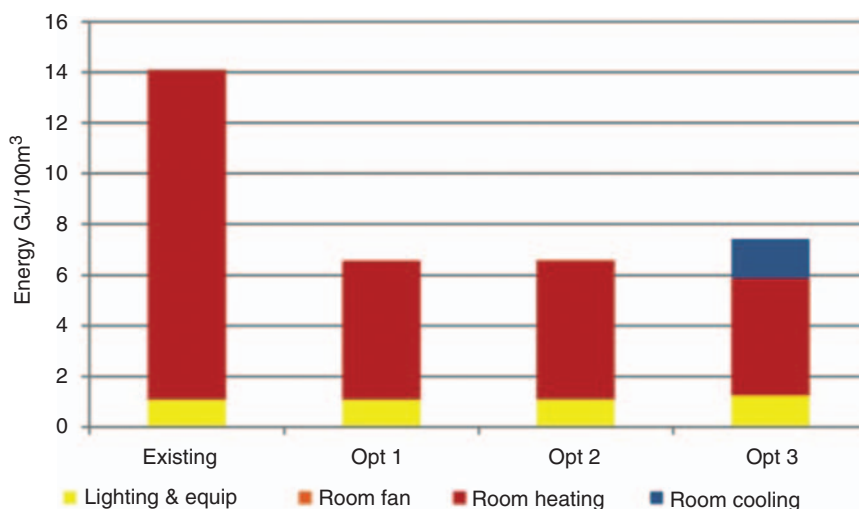
wards at Bradford, a model was developed in the IES dynamic thermal modelling software. Ward 9 was modelled with three zones; a summary of the assumed existing characteristics is presented in Table 3. The window opening duration and heating profiles were adjusted such that the model's temperature predictions matched the values measured during the 69-day period. The 2010 weather file for dynamic simulation was created by the University of Exeter using the Bingley weather data, the closest available station. This contained all the hourly values needed in for thermal modelling. Most parameters such as dry bulb temperature, wet bulb temperature, relative humidity, wind velocity, wind direction and pressure were taken directly from the observed data. The diffuse solar radiation, global solar radiation and direct solar radiation were derived from Bingley cloud cover as explained in CIBSE TM48.<sup>22</sup> The year 2010 was relatively cool with just 3 h when the ambient temperature exceeded 24°C compared to 57 h in the current CIBSE test reference year for the location. For the 69-day period for which measured data was available, the model predicted zero internal hours above 28°C air temperature, which is in line with the monitored results. Further, predicted maximum, mean daytime and mean night-time operative temperatures were 28.2°C, 23.6°C and 22.9°C, respectively, very similar to the monitored maximum, mean daytime and mean night-time operative temperatures were 28.2°C, 23.4°C and 22.7°C.

The model predicted 179 annual hours above the BSEN15251 Cat I upper temperature threshold. This is well within the BSEN15251 allowable limit of 5% of hours above the Cat I upper threshold (i.e. 438 h per year). The predicted energy demand in 2010 was 14 GJ/100 m<sup>3</sup> (Figure 13), with over 90% of this being for space heating. Before comparing this with the NHS energy target it is important to note that the predicted figures only include energy for space heating and

**Table 3** The characteristics of existing and proposed refurbishment options for Ward 9.

| Description | Wall<br>'U' value<br>(W/m <sup>2</sup> K) | Roof<br>'U' value<br>(W/m <sup>2</sup> K) | Volume<br>(m <sup>3</sup> ) | Window opening and shading                                       | Upper level trickle vent            | Space conditioning strategy                 | Set point temperature (°C)                           |
|-------------|---|---|-----------------------------|--|-------------------------------------|---|--|
| Existing    | 1.0                                       | 0.3                                       | 958                         | Middle pane opened but no shading                                | NA                                  | Perimeter heating only                      | Winter: 23<br>Summer: 22                             |
| Opt-1       | 0.2                                       | 0.1                                       | 958                         | All three window panes are opened and shading above the two pane | NA                                  | Perimeter heating only                      | Winter: 23<br>Summer: 22                             |
| Opt-2       | 0.2                                       | 0.1                                       | 958                         | All three window panes are opened and shading above the two pane | NA                                  | Perimeter heating and ceiling fan           | Winter: 23<br>Summer: 22                             |
| Opt-3       | 0.2                                       | 0.1                                       | 868                         | All windows are fixed and shading above the two pane             | 25 no. 100 mm diameter louvre units | Heating and cooling through radiant ceiling | Heating Winter: 26<br>Summer: 21; Cooling Summer: 16 |

**Note:** In all cases the floor area is 274 m<sup>2</sup>; In all cases total window area is 60 m<sup>2</sup>; In the existing, opt-1, and opt-2 for heating, heat output ramped down from 100% when the ambient temperature,  $T_a \leq 15^\circ\text{C}$  to 90% at  $T_a \geq 15^\circ\text{C}$ ; In opt-3, for heating, heat output ramped down from 100% when the ambient temperature,  $T_a \leq -3^\circ\text{C}$  to zero at  $T_a \geq 15^\circ\text{C}$ ; In opt-3, for cooling, heat output ramped up from zero when  $T_a \leq 15^\circ\text{C}$  to 100% at  $T_a \geq 18^\circ\text{C}$ ; It is assumed that the occupants open the window and maximum opening of 100 mm; In existing, opt-1 and opt-2 windows open 10% when the indoor temperature  $T_{in} \geq 23^\circ\text{C}$  and ramp to 100% at  $T_{in} \geq 25^\circ\text{C}$ , but the windows completely close when the ambient temperature,  $T_a \leq 12^\circ\text{C}$  and  $T_a \leq 15^\circ\text{C}$  in summer and winter, respectively; In opt-2 the fan comes into operation when the indoor temperature,  $T_{in} \geq 26^\circ\text{C}$ .



**Figure 13** Predicted energy consumption pattern of the existing building and proposed refurbishment options during the year 2010.

lighting of the modelled area. However, energy targets cover all end uses, including hot water provision, catering, medical equipment, small power, retail space, pumps, controls, lifts, etc. Across all UK hospitals these other elements would be about 44% of total energy demand.<sup>6</sup> Without detailed data for Bradford specifically this estimate will be used here; i.e. total demand for the nightingale wards and associated provision is taken as 1.78 times the predicted values. Notwithstanding this uplift, the adjusted energy demand<sup>c</sup> of about 25 GJ/100 m<sup>3</sup> is well below the NHS target of 55–65 GJ/100 m<sup>3</sup> for refurbished buildings and, indeed, below the target of 35–55 GJ/100 m<sup>3</sup> for new buildings.

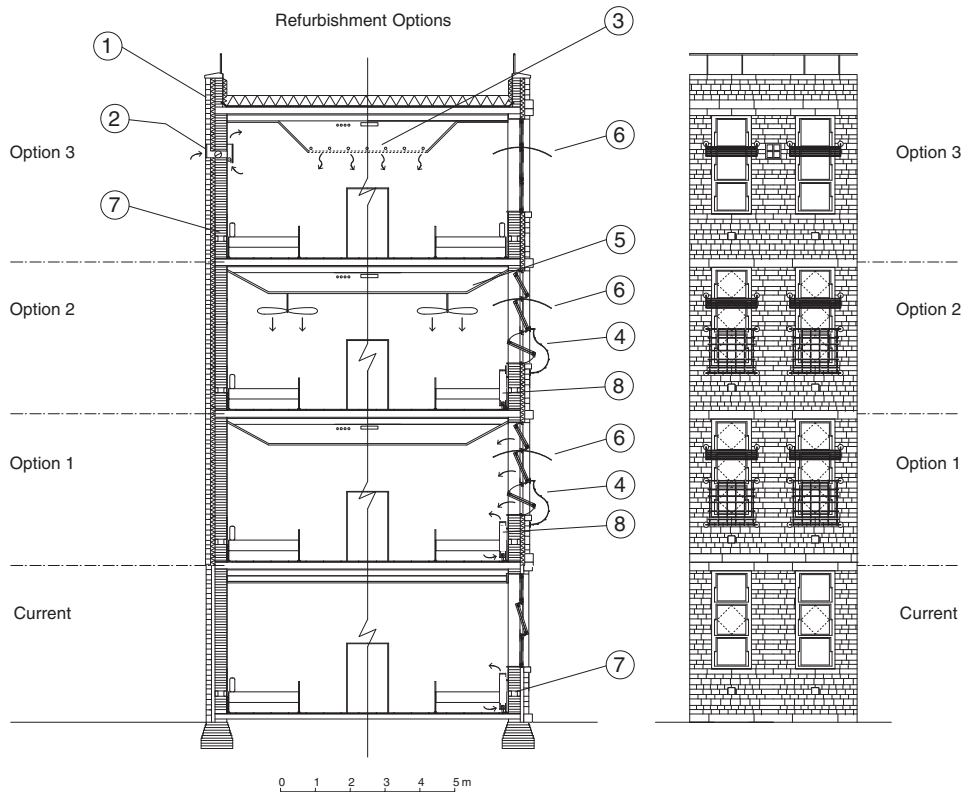
Concerning CO<sub>2</sub> emissions, the predicted value is about 30 kgCO<sub>2</sub>/m<sup>2</sup> (Figure 14), which, using the crude adjustment noted above, would uplift to about 53 kgCO<sub>2</sub>/m<sup>2</sup>. The CIBSE provide, in Technical Memorandum TM46,<sup>22</sup> the benchmarks used for determining the operational rating

of buildings.<sup>d</sup> The TM46 benchmark for 'Hospitals; clinical and research' is 129.3 kgCO<sub>2</sub>/m<sup>2</sup>, weather adjusted to 2010 gives a value of 147.9 kgCO<sub>2</sub>/m<sup>2</sup>; with a recorded 2877 heating degree-days 2010 for the West Pennine region, which is much cooler than the typical UK average. The predicted emissions figure for the modelled ward is clearly much less than the benchmark value.

Considering the NHS stock as a whole, these results would suggest that Nightingale wards are, relative to some other forms of ward, relatively efficient. For example, a recent paper studying the demand of a 1960s tower building with hybrid ventilation predicted an energy demand for space conditioning only of 101 GJ/100 m<sup>3</sup> (cf. 14 GJ/100 m<sup>3</sup>).<sup>23</sup> These results begin to show how measurement and modelling might combine to provide strategic guidance on how

<sup>c</sup>25 ≈ 14 × 1.78 GJ/100 m<sup>3</sup>.

<sup>d</sup>These are the mandatory 'energy ratings' shown on the Display Energy Certificates that must be displayed in all UK public buildings over 1000 m<sup>2</sup>. The certificates rate buildings on an A to G scale using the TM46 values as the benchmark.



**Figure 14** Section showing existing configuration and refurbishment options.

1: Remove stone, insulate (125mm), replace stone, add insulation to roof to 300mm o/a; 2: High level 100mm air inlet ducts through solid wall with radiant panel to ceiling; 3: Radiant panel for hot and cold water; 4: Opening lights in existing window openings with guards as needed externally; 5: Introduce slow wide-span fans above beds; 6: Shading and lightshelves of perforated white powder-coated aluminium to suppress glare and achieve more even daylight distribution; 7: Seal vents and remove radiators/convectors to counter cleaning problem; 8: Perimeter heating is retained below the windows.

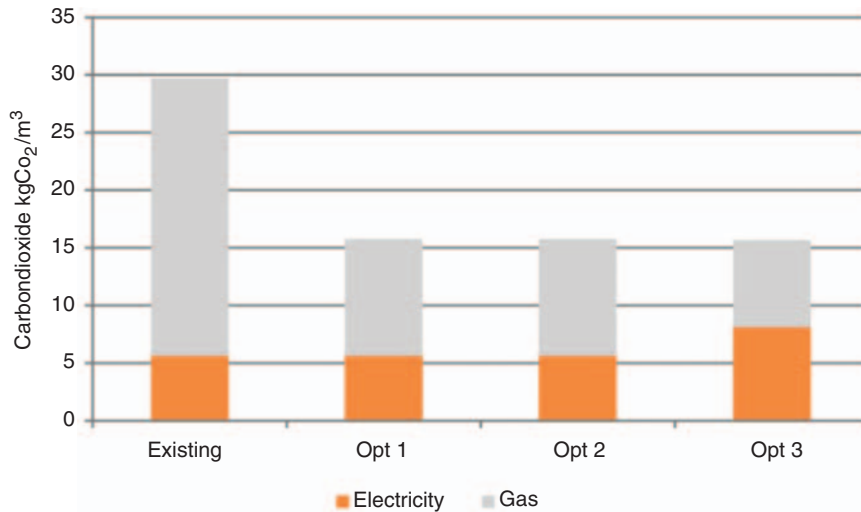
best to reduce the energy demand of the NHS stock.

## 5 The refurbishment options and performance in current climate

Current economic circumstances place a particular premium on light-touch refurbishment of NHS sites; similarly, a wholly reasonable concern to improve the patient experience also means that cosmetic changes can be favoured over more substantial interventions. In addition, Trusts are reluctant to lose capacity and have concerns about construction noise and dust transmission.<sup>23</sup>

Three refurbishment options have been devised for the Nightingale wards. The characteristics of all three options are presented in Table 3 and Figure 14, and are described in more detail below. For each, the predicted annual energy demands and CO<sub>2</sub> emissions of the refurbished Nightingale ward<sup>c</sup> were predicted using IES and the Bradford 2010

<sup>c</sup>By modelling one ward rather than the whole building, calibration against the measured data was possible and matters related to control of ventilation and the consequential impact on temperatures could be explored carefully. Multiple simulations could be undertaken easily, because changes to the simple model could be made rapidly. The relative performance of the refurbishment options is valid.



**Figure 15** Predicted carbon dioxide release pattern for different options during the year 2010.

weather file (i.e. Bingley) and compared with the NHS and TM46 benchmarks (Figures 13 and 15). The internal temperatures were predicted for the summer period, 1 May to 30 September, and it was assumed that during the winter part of the year there would be no overheating due to elevated ambient temperatures and solar gain. The results were assessed using the CIBSE overheating criterion for night-time and the HTM03 criterion for all hours, except the option with the fan (Option 2), which is not amenable to analysis using HTM03. For the two refurbishment options that eschew mechanical cooling, the BSEN15251 approach was used to assess the internal temperatures; the third option included radiant ceiling cooling (Table 3).

It is important to note that in all the simulations, the ventilation, heating and cooling control strategies (Table 3) were devised with the provision of overall summertime thermal comfort as the priority. Less attention was given to the impact of the chosen control strategies on the night-time temperatures or the annual energy demand and CO<sub>2</sub> emissions. There was no attempt to adjust the

control strategies or heating and cooling set points in the calibrated model, though clearly such adjustments may well be made in practice post refurbishment by facilities managers.

Option 1 removes the outer layer of stone, adds 125 mm of insulation and for specific local planning expectations the stone is replaced. In less sensitive circumstances external render and face-fixed insulation would deliver similar performance. The existing insulation to the roof is increased to an overall depth of 300 mm. All three lights in every window are made operable to a maximum allowable opening of 100 mm (though the provision of a guard to the lower window, as shown, would allow full opening). All windows are shaded with a fixed shade to limit solar gain on the glass. Perimeter heating is maintained below the windows. The suspended ceiling was modelled at 600 mm below the soffit (this is the condition prior to October 2010).

With this option the space heating demand dropped from about 14 GJ/100 m<sup>3</sup> to an extremely low value of about 5 GJ/100 m<sup>3</sup>, lighting and small power gains remained unchanged. The CO<sub>2</sub> emissions were about

**Table 4** Summary of predicted internal operative and air temperatures for May to September, 2010 Bradford weather.

| Option      | Maximum temperature (°C)<br>(24 hours) | Mean Temperature (°C)<br>(24 hours) | Minimum temperature (°C)<br>(24 hours) | Mean night-time <sup>a</sup> temperature (°C) | HTM03: Total hours <sup>b</sup> over 28°C | CIBSE: Night-time <sup>1</sup> hours over 26°C | BSEN15251: Total hours above Cat I Upper limit | BSEN15251: Total hours above Cat II Upper limit |
|-------------|--|-------------------------------------|--|---|---|--|--|---|
| <b>2010</b> |  |                                     |  |   |   |  |  |   |
| Existing    | 29.0                                   | 23.0                                | 21.6                                   | 22.5  | 4   | 3  | 179  | 47  |
| Opt-1       | 27.4                                   | 23.2                                | 21.9                                   | 22.8  | 0   | 0  | 196  | 25  |
| Opt-2       | 26.2                                   | 23.2                                | 21.9                                   | 22.8  | 0   | 0  | 192  | 16  |
| Opt-3       | 26.8                                   | 23.0                                | 20.8                                   | 22.5  | 0   | 0  | na   | na  |

<sup>a</sup>Night-time hours are 21:00 to 06:00; <sup>b</sup>Simulated hours are for May to September (153 days, 3672 hours); The HTM03 threshold is based on air temperature and rest are based on operative temperature.; It is assumed that during the winter half of the year (October to April) the space will not overheat due to elevated ambient temperatures and solar gains. The limiting overheating values are therefore: HTM03, >50 h over 28°C; BSEN15251, >438 h above category upper thresholds and CIBSE, >37 night-time hours (1%) over 26°C). These were not exceeded by any of the options.

15 kgCO<sub>2</sub>/m<sup>2</sup>. Clearly the added insulation has an impact. There were just 196 h above the BSEN15215 Cat I upper threshold, which represents about 5.3% of the total for the summer (May to September) period modelled (Table 4). Assuming that the heating system is appropriately controlled during the winter time so there is no overheating, then over a year there will be just 2% of hours over the Cat I envelope; which is well within a suggested BSEN15251 limit of 5%. The small increase in the overall incidence of high temperatures is, presumably, due to the fabric insulation, which increases the mean ward temperature by 0.2°C compared to the existing condition (Table 4). Rather importantly, however, the refurbishment reduces the impact of higher ambient temperatures and solar gain, resulting in a reduction in the peak temperatures (Table 4). This effect may well yield benefits as the climate warms (see below). Full removal of the suspended ceiling might result in greater benefits still.

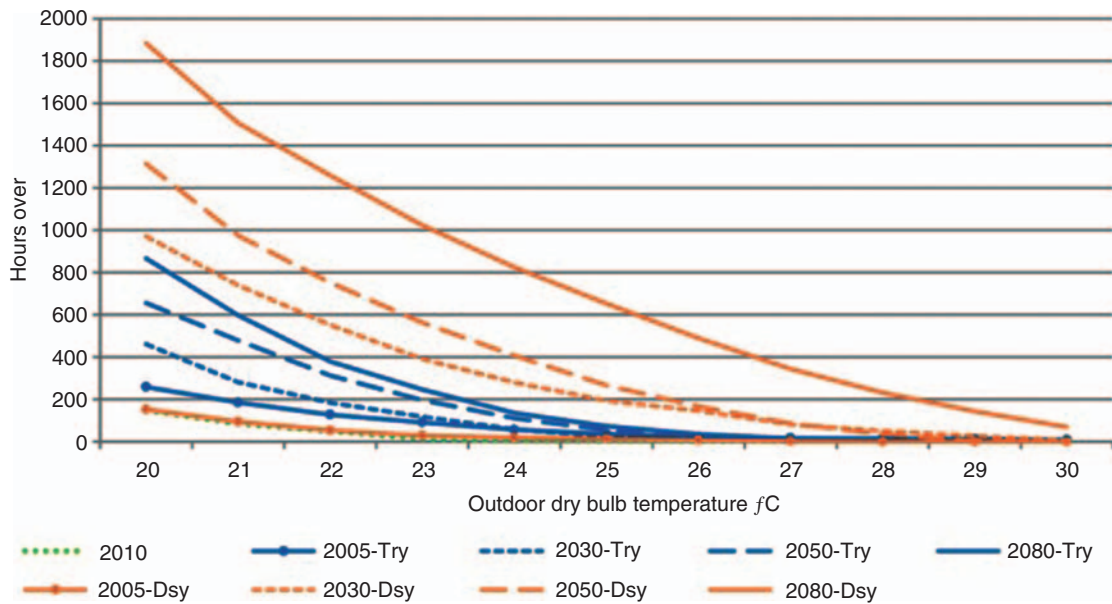
Option 2 is identical to option 1 in terms of wall and roof insulation, window pattern and perimeter heating, but a low-velocity large sweep fan is installed. The model assumes four ceiling mount fans for each zone. These are slow fans, 0.3 m/s air speed, which is well inside the allowable upper limit of 0.8 m/s,

giving an operative temperature depression of 1.2°C, the assumed fan power is 70 W per fan.

The addition of the slow fan resulted in very little change to the occurrence of elevated summertime temperatures, there being about 5.2% of summertime hours above the Cat I upper threshold. Neither was there much difference in the energy demand and CO<sub>2</sub> emissions. This is because the predicted internal temperature rarely exceeded 26°C, the temperature at which the fans were set to switch on. In a warmer future, fans may become useful in hospitals in more northerly UK locations, like Bradford (see below).

Option 3 has the same insulation standards and shading as the other options, but seals all the windows. It introduces 100 mm diameter high-level air inlets above each bed space, between each window, with a damper, and a simple convective heating device fixed to the internal face to enable supply air to be pre-heated and/or recirculation within the space. Primary heating and cooling is delivered through the installation of radiant ceiling panels (Table 3). The addition of radiant cooling eliminates entirely the risk of overheating (Table 4). Clearly it would be important to maintain the room wet bulb temperature above the dew point to avoid condensation.





**Figure 16** Frequency of occurrence of outdoor temperature above 20°C.

## 6 Performance in a future climate

To examine the resilience of the existing Nightingale wards and the three refurbishment options to climate change, internal temperatures were predicted for current and future typical and extreme temperature years as represented by Test Reference Years (TRY), which contain monthly data that typifies the location and Design Summer Years (DSY), which are a whole year with abnormally high temperatures. The standard temperature files for the current weather in Bradford, the Test Reference Year (called 2005TRY) and the Design Summer Year (called 2005DSY), were developed by the University of Exeter using the customary CIBSE methods as described by Levermore and Parkinson.<sup>24</sup> The years were derived from hourly data recorded between 1983 and 2004 at the Bingley weather station, the diffused, direct and global radiation were derived as explained in the section 4.2. Other parameters were directly sourced and the missing values

are interpolated. The 2005TRY was created by chaining the most typical January to the most typical February, etc and then smoothing the inter-month joins. Likewise the standard approach to producing a DSY was used. Based on the mean temperature recorded between April and September, 2004 was chosen from the 22-year string as it was the third hottest and so represents the 90 percentile year; i.e. only one year in 10 will be hotter.

The future weather years were created from the UKCP09 future climate projections assuming an A1B global emissions development scenario<sup>f</sup> using the method evolved by the University of Exeter for the 'Prometheus' research project. The method samples the 3000 probabilistic weather files generated for each future time frame using, to a large extent, the standard selection method.<sup>20</sup> This produced TRYs and DSYs for the 30-year

<sup>f</sup>A globalised, technologically advanced world in which energy production includes a broad portfolio of fossil-fuel and non-fossil-fuel sources.

periods centred around 2030, 2050 and 2080 for the 5 km grid square covering Bradford.<sup>g</sup> The method used has been fully described by Eames et al.,<sup>25</sup> and is summarised in Lomas and Giridharan.<sup>19</sup>

The frequency of occurrence of temperatures above 20°C is shown for the year of measurement 2010 and for each of the four TRYs and DSYs in Figure 16. It can be seen that the occurrence of higher temperatures increases gradually in the TRYs but quite rapidly in the DSYs. Thus, as the years go by, the difference between the temperatures in typical and extreme years is accentuated.

The temperatures in the existing Nightingale ward and in the refurbished ward were predicted using the IES modelling system.<sup>19</sup> Simulations were undertaken with all eight weather years and predictions of the likely air and operative temperatures were compared with the CIBSE, HTM03 and BSEN15251 overheating criteria (Table 5), as appropriate; HTM03 is not amenable to evaluation of the effect of fans and the BSEN15251 standard does not apply to mechanically cooled buildings. Although the simulations were undertaken just for the summer period (May to September) overheating was assessed on an annual basis, it being assumed that overheating due to elevated ambient temperatures and solar gains would not occur during the remainder of the year.

The internal heat gains, window opening strategy and control strategies (e.g. for the cooling option) were the same as for the 2010 analyses described above. In practice facilities managers might adjust the control regimens in the light of year-on-year changes in the climate. The results presented do not therefore represent optimal performance. Nevertheless, they clearly show the relative performance of the different options and give a very good indication of their inherent

resilience. This approach is consistent with that taken previously by the authors.<sup>23</sup>

The results clearly indicate that neither the existing or refurbished building will overheat in typical years, as judged by the HTM03 and BSEN15251 criteria but in the 2050s warmer night-time temperatures may be experienced (although these might be ameliorated easily with a refined window opening regimen). In the extreme temperature years (i.e. the DSYs), however, HTM03 shows overheating occurs in the existing building and with refurbishment option 1 as early as the 2030s, the frequency of overheating increases thereafter.

The BSEN15251 approach, which accommodates human adaptation to the prevailing ambient conditions and thus our preference for warmer conditions in free-running buildings as the ambient conditions become warmer, indicates that the refurbishment options that do not incorporate cooling will remain comfortable in both typical and extreme years right up to 2080s. The effect of the fan in reducing the hours of elevated temperatures is clear (compare Option 1 and Option 2). The existing building is, though, predicted to overheat based on the Cat I thresholds by the 2050s. The addition of the mechanical cooling ensures there is no overheating in either typical or extreme temperature years right up to the 2080s.

In summary therefore it would seem that the inherent resilience of the Nightingale wards, together with the northerly location of Bradford (and thus modest summertime temperatures even in the 2080s), enables passive retrofit to succeed in producing a building that is comfortable until towards the end of this century.

## 7 Conclusions

What might be regarded as an archaic and redundant hospital building type, problematic in its plan geometry, reveals a degree of resilience to summertime overheating in

<sup>g</sup>This is the adjacent 5 km grid to the one containing the Bingley meteorological station.

**Table 5** Summary of predicted internal operative and air temperatures for May to September, current, and future Bradford climate (Bingley).

| Refurbishment TRY<br>Option |      | DSY                      |              |   |  |   |  |   |                          |                          |   |  |   |  |   |  |
|-----------------------------|------|--------------------------|--------------|---|--|---|--|---|--------------------------|--------------------------|---|--|---|--|---|--|
|                             |      | Maximum temperature (°C) | Minimum (°C) | Mean temperature night-time <sup>a</sup> (°C) | HTM03: Total hours <sup>b</sup> over 28 °C | CIBSE: Night-time <sup>b</sup> hours over 26 °C | BSEN15251: Total hours above cat I upper limit | BSEN15251: Total hours above cat II upper limit | Maximum temperature (°C) | Minimum temperature (°C) | Mean temperature night-time <sup>a</sup> (°C) | HTM03: Total hours <sup>b</sup> over 28 °C | CIBSE: Night-time <sup>b</sup> hours over 26 °C | BSEN15251: Total hours above cat I upper limit | BSEN15251: Total hours above cat II upper limit |  |
| 2005                        |      |                          |              |   |  |   |  |   |                          |                          |   |  |   |  |   |  |
| Existing                    | 33.2 | 21.7                     | 22.8         | 84  | 48   | 301   | 142  | 29.1  | 21.7                     | 22.7                     | 6   | 2  | 137   | 30   |   |  |
| Opt-1                       | 31.2 | 21.9                     | 23.0         | 21  | 10   | 283   | 87   | 27.8  | 21.9                     | 23.0                     | 0   | 0  | 213   | 57   |   |  |
| Opt-2                       | 30.0 | 21.9                     | 23.0         | na  | 3  | 243   | 56   | 26.6  | 21.9                     | 23.0                     | na  | 0  | 200   | 37   |   |  |
| Opt-3                       | 28.3 | 21.2                     | 22.6         | 5   | 0  | na  | na   | 26.6  | 21.8                     | 22.7                     | 0   | 0  | na  | na   |   |  |
| 2030                        |      |                          |              |   |  |   |  |   |                          |                          |   |  |   |  |   |  |
| Existing                    | 30.6 | 21.8                     | 23.3         | 25  | 29   | 283   | 83   | 32.5  | 21.8                     | 23.9                     | 210   | 123  | 421   | 228  |   |  |
| Opt-1                       | 28.4 | 22.0                     | 23.2         | 3   | 1  | 197   | 59   | 30.5  | 22.0                     | 23.4                     | 77  | 36   | 177   | 76   |   |  |
| Opt-2                       | 27.2 | 22.0                     | 23.2         | na  | 0  | 173   | 46   | 29.3  | 22.0                     | 23.4                     | na  | 14   | 83  | 29   |   |  |
| Opt-3                       | 27.1 | 21.6                     | 22.7         | 0   | 0  | na  | na   | 27.8  | 21.3                     | 22.7                     | 1   | 0  | na  | na   |   |  |
| 2050                        |      |                          |              |   |  |   |  |   |                          |                          |   |  |   |  |   |  |
| Existing                    | 30.7 | 21.8                     | 23.5         | 66  | 63   | 370   | 140  | 33.0  | 21.8                     | 24.6                     | 364   | 261  | 648   | 333  |   |  |
| Opt-1                       | 28.9 | 22.0                     | 23.2         | 6   | 0  | 132   | 26   | 30.2  | 22.1                     | 23.7                     | 93  | 33   | 177   | 67   |   |  |
| Opt-2                       | 27.7 | 22.0                     | 23.2         | na  | 0  | 84  | 11   | 29.0  | 22.1                     | 23.7                     | na  | 7  | 46  | 5  |   |  |
| Opt-3                       | 28.0 | 20.9                     | 22.7         | 1   | 0  | na  | na   | 27.8  | 21.2                     | 22.9                     | 1   | 0  | na  | na   |   |  |
| 2080                        |      |                          |              |   |  |   |  |   |                          |                          |   |  |   |  |   |  |
| Existing                    | 30.8 | 21.7                     | 23.8         | 95  | 90   | 320   | 104  | 36.1  | 21.9                     | 25.4                     | 812   | 505  | 974   | 619  |   |  |
| Opt-1                       | 28.5 | 22.0                     | 23.3         | 13  | 5  | 58  | 6  | 33.8  | 22.2                     | 24.2                     | 350   | 143  | 399   | 200  |   |  |
| Opt-2                       | 27.3 | 22.0                     | 23.3         | na  | 0  | 22  | 0  | 32.6  | 22.2                     | 24.1                     | na  | 58   | 182   | 73   |   |  |
| Opt-3                       | 27.1 | 20.9                     | 22.6         | 0   | 0  | na  | na   | 29.7  | 21.3                     | 23.1                     | 51  | 16   | na  | na   |   |  |

Notes: <sup>a</sup>Night-time hours are 21:00 to 06:00. <sup>b</sup>Simulated hours are for May to September (153 days, 3672 h); HTM03 threshold is based on air temperature and rest is based on operative temperature; The grey shows where limiting criteria are exceeded. The darker grey indicates where the exceedance is deemed important in that it could not be easily corrected by refining the control strategy. It is assumed that during the winter (October to April) the space will not overheat due to elevated ambient temperatures and solar gains so the exceedances limits are HTM03, >50 h over 28°C, BSEN15251, >438 h above category upper threshold and CIBSE, >37 night-time hours (1%) over 26°C.

Northern England. The narrow sections, high floor to ceiling heights, and the potential for cross ventilation, plus the mass inherent in the masonry and concrete construction, deliver the basic resilience. Health and safety concerns in the restriction of opening areas have compromised this quality to some extent but perhaps more appropriate control strategies can boost or enhance the innate resilience of the type. Trusts may wish to review the expected life of these buildings, which make up a significant proportion of the 22% of NHS hospital buildings that pre-date 1948.

Modelling the three adaptation strategies on the future climate basis and using the envelopes of the adaptive comfort standard BS EN 15251 as a basis for evaluation, reveals that even modest refurbishment comprising insulation, shading and improved natural ventilation (Option 1) will ensure that in typical years the wards remain comfortable right through to the 2080s (i.e. temperatures are well within the most stringent, Cat I envelope). Complete removal of the suspended ceilings factored into the model might improve performance yet more. The addition of a slow fan (Option 2) further reduces the hours outside the Cat I envelope. In extreme temperature years there are a greater number of hours outside the Cat I envelope, but fewer with the fan installed, but in neither case would these exceedances be of concern. In contrast, in extreme temperature years, by the 2030s the unrefurbished wards will experience an unacceptable number of hours outside the Cat I threshold; i.e. they will overheat. The provision of cooling (Option 3) ensures that overheating is eliminated entirely, but will have first cost, maintenance and energy demand implications, which the passive options do not.

The provision of simple slow-rotating fans would therefore seem to have material benefit to extending comfort in warmer conditions but the authors note from their discussions

with various Private Finance Initiative designer/developer consortia, planning real hospitals, that there is a marked resistance to this simple innovation. The anxieties expressed relate to the facilities management issue of cleaning and infection control.

A comprehensive comparative costing exercise across all the DeDerHECC case study buildings and the refurbishment options investigated will be completed by the close of the project and the subject of a separate paper. Having demonstrated the basic resilience of the type, further work will also explore the potential for ward layouts that achieve greater levels of privacy and dignity, or for possible alternative uses for these buildings within the hospital campus.

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## References

- 1 National Health Service Information Centre. Hospital estates and facilities statistics, <http://www.hefs.ic.nhs.uk/ReportFilter.asp> (2010, accessed 25 May 2011).
- 2 Department of Health. Privacy and dignity, [http://webarchive.nationalarchives.gov.uk/+www.dh.gov.uk/en/Managingyourorganisation/Workforce/Leadership/Healthcareenvironment/DH\\_4116444](http://webarchive.nationalarchives.gov.uk/+www.dh.gov.uk/en/Managingyourorganisation/Workforce/Leadership/Healthcareenvironment/DH_4116444) (2010, accessed 21 July 2011).
- 3 Department of Health. National Service Framework – for Older People, [http://www.dh.gov.uk/prod\\_consum\\_dh/groups/dh\\_digitalassets/@dh/@en/documents/digitalasset/dh\\_4071283.pdf](http://www.dh.gov.uk/prod_consum_dh/groups/dh_digitalassets/@dh/@en/documents/digitalasset/dh_4071283.pdf) (2001, accessed on 21 July 2011).
- 4 Hinitt I, Noakes CJ. Peruvian lessons to inform Bradford pilot. *Health Estates J* 2008; 62/5: 31–35.
- 5 National Health Service Sustainable Development Unit. *Saving carbon, improving health* 2008; London, NHS Publications.
- 6 Department of Health. *Health Technical Memorandum 07-02: EnCO2de: making energy work in healthcare* 2006; London, The Stationery Office.
- 7 Department of Health. Estates Returns Information Collection (ERIC), <http://www.dh.gov.uk> (2008).
- 8 Department of Health. *Heatwave plan for England: Protecting health and reducing harm from extreme heat and heatwaves* 2011; London, NHS Publications.
- 9 Lomas KJ, Ji Y. Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards. *Energy Build* 2009; 41/6: 629–653.
- 10 Department of Health. *Health Technical Memorandum 03-01: Specialised Ventilation for Healthcare Premises* 2007; London, The Stationery Office.
- 11 Short CA, Al-Maiyah S. Design strategy for low-energy ventilation and cooling of hospitals. *Build Res Inform* 2009; 37/3: 264–292.
- 12 Richardson H. *English Hospitals 1660-1948* 1998; London, RCHME.
- 13 Gilkeson CA, Noakes CJ, Sleight A, et al. Simulating pathogen transport within a naturally ventilated hospital ward. In: *International conference on computational fluid dynamics*, Paris, 27-29 July 2011.
- 14 Camargo-Valero MA, Gilkeson CA, Noakes CJ. Tracer-gas technique as a surrogate method for tracking airborne pathogen transport in indoor environments. *Indoor Air 2011* Austin, Texas, 4–10 June 2011.
- 15 Banham R. *Architecture of the well-tempered environment* 1969; London, Architectural Press.
- 16 Firth G. *Bradford charity and the public purse* 2001; Bradford, Bradford Teaching Hospitals NHS Trust.
- 17 Nuffield Provincial Hospitals Trust. *Studies in the functions and design of hospitals* 1955; Oxford, Oxford University Press.
- 18 Health Facilities Scotland. *Scottish Health Technical Memorandum 55: Windows* 2006; Edinburgh and Glasgow, Health Facilities Scotland.
- 19 Lomas KJ and Giridharan R. Thermal comfort standards, measured internal temperatures and resilience to climate change of free-running buildings: a case study of hospital wards. *Build Environ* 2012 (in press).
- 20 CIBSE. *Guide A: environmental design* 2006; London, CIBSE.



- 21 British Standards Institution. *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment lighting and acoustics* 2007; Brussels, British Standard BSEN15251.
- 22 CIBSE. *The use of climate change scenarios for building simulation: the CIBSE future weather years* 2008; London, CIBSE.
- 23 Short CA, Lomas, KJ, Giridharan R, et al. Building resilience to overheating into UK hospitals within the constraint of the national carbon reduction target: adaptive strategies for 1960s buildings. *Build Environ* 2012 (in press).
- 24 Levermore J, Parkinson JB. Analyses and algorithms for new Test Reference Years and Design Summer Years for the UK. *Build Serv Eng Res Technol* 2006; 27/4: 311–326.
- 25 Eames M, Kershaw T, Coley D. On the creation of future probabilistic design weather years from UKCP09. *Build Serv Eng Res Technol* 2011; 32/2: 127–142.
- 26 Stone JE. *Hospital organisation and management* 1952; London, Faber and Faber.